Terahertz Pioneer: Federico Capasso

"Physics by Design: Engineering Our Way Out of the THz Gap"

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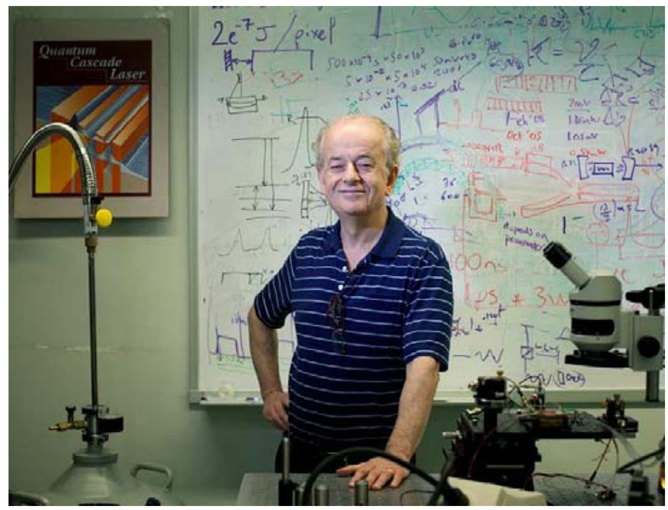
FEDERICO CAPASSO[1] credits his father, an economist and business man, for nourishing his early interest in science, and his mother for making sure he stuck it out, despite some tough moments. However, he confesses his real attraction to science came from a well read children's book—*Our Friend the Atom* [1], which he received at the age of 7, and recalls fondly to this day. I read it myself, but it did not do me nearly as much good as it seems to have done for Federico!

Capasso grew up in Rome, Italy, and appropriately studied Latin and Greek in his pre-university days. He recalls that his father wisely insisted that he and his sister become fluent in English at an early age, noting that this would be a more important opportunity builder in later years. In the 1950s and early 1960s, Capasso remembers that for his family of friends at least, physics was the king of sciences in Italy. There was a strong push into nuclear energy, and Italy had a revered *first son* in Enrico Fermi. When Capasso enrolled at University of Rome in 1969, it was with the intent of becoming a nuclear physicist.

The first two years were extremely difficult. University of Rome had very high standards—there were at least three faculty members who had personally worked with Fermi—and teaching did not include much hand holding. When he began his thesis work with Francesco De Martini, a distinguished researcher in nonlinear optics who had worked with Charles Townes at MIT, he was told simply "Take this blueprint, build a ruby laser and see me in six months." Remarkably, when he came back with a working laser, De Martini sent him back to the lab with the assignment, "Now build a heat exchanger for our argon laser." Despite a strong desire to let De Martini hear what he really felt about this request, he went back to the engineering shop and designed an oversized cooler that not only worked on the argon laser, but many other more powerful lasers in the lab, thus endearing him to his fellow researchers.

As already mentioned, the university crossing was not one that Capasso easily traversed. The 22 successive oral and written



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exams, lack of grade inflation and rigorous course load, had Capasso rethinking his career choice after two years. Here his mother came to the rescue, and insisted that he keep struggling while banishing all thoughts about quitting. In his third year, things finally began to click, and ultimately he came out of University of Rome with several nice papers [2]–[5], and a focus in nonlinear optics, rather than nuclear physics.

Perhaps this somewhat painful, although ultimately triumphant start in science, along with a very hierarchical academic system in Italy, contributed to Capasso's decision to go into industry after completing his degree. After a short Post-Doctoral appointment, he took up a permanent position as a research physicist at Fondazione Bordoni in Rome, starting in 1974. Fondazione Bordoni was one of a number of government institutions around Europe that specialized in communications, and as such, these were commonly referred to as "Post-Office Laboratories." Capasso started working on optical transmission, including amplifiers, liquid core fibers and mode theory [6]–[9].

Despite the appeal of a secure permanent position at Bordoni, Capasso was restless and longed for an opportunity to go abroad. The US was especially attractive, and after marrying his wife of 37 years, Paola, in 1976, he applied for and received a Rotary Fellowship that supported him to work in a research institution outside of Italy for nine months. However, the terms of the fellowship were that the Award Committee chose the laboratory, taking into account the applicant's skills, as well as his preferences. Capasso's fluency in English was turning out not to be the gift his father had wished, as the committee was about to send him to Belfast, Northern Ireland, at a time when this particular

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[1] Frederico Capasso works in Pierce Hall, across from the Peabody Museum at Harvard University, Cambridge, MA. His enthusiasm about his past and current research work, his teaching, his students, his numerous colleagues spanning all scientific disciplines, his new company, his professional ideals, and his scientific goals, is completely contagious. Talking in his office for more than four and a half hours on a brisk Thursday morning in mid-November, we covered topics from the Casimir force to quantum cascade lasers to flat optics, to the nature and purpose of scientific research, and the philosophy of teaching. The result is this short biographical article.

city would not have been the first choice of a Catholic man with a new young wife. After an appeal, the Rotary Fellowship was instead applied to an alternate English speaking country—the USA—to a very desired slot at Bell Laboratories. Relieved, Capasso and his wife gleefully set out for Holmdel, NJ, USA, in the fall of 1976.

At Bell Laboratories at this time, there was an ongoing effort to extend fiber systems out to 1.3 microns and beyond, where transmission losses were at a minimum and semiconductor lasers, especially GaAs, were making great strides. Charles Kao (2009 Nobel prize in Physics) had just published his ground-breaking paper [10] on eliminating impurities to enable super low loss fibers, and the potential for compact optical communications systems was on many people's minds. Capasso joined a semiconductor laser group that was working towards enabling long wavelength fiber communications. He had designs on staying in the US, and he was pretty certain that, as just one of many already distinguished physicists working on laser sources, he would not be able to distinguish himself in the short time he had available under the Rotary Fellowship. A colleague suggested that perhaps he might be better served if he turned his attention to long wavelength detectors, which were not playing as *visible* a role in the quest for long range optical communications links.

Silicon was being used at shorter wavelengths, and although germanium worked at 1.1 microns, it was very noisy. It was generally known that silicon photodiodes had low noise because of the efficient impact ionization process, wherein electrons could create electron–hole pairs much more effectively than holes could, thus assuring unidirectional avalanche multiplication in an applied field. In III–V materials however, the ratio of the impact ionization rate by electrons and by holes is much closer to unity, degrading performance. Capasso and a small group of physicists at Bell, including Jim Gordon (co-inventor of the MASER [11]), began meeting to discuss ways in which the newly engineered III-V materials might be designed to create much higher electron-to-hole impact ionization ratios.

Capasso began by looking closely at impact ionization mechanisms in various material systems and discovered new band structure phenomena [12], [13]. These results earned him a much coveted Bell Labs Member of Technical Staff position at the Murray Hill laboratory, which Capasso accepted at the end of 1977 after resigning from Fondazione Bordoni.

Capasso notes with pride that, this type of position at Bell was not granted without trial. Before he received his job offer, he was required to give a seminar on his accomplishments of his prior two years as a Bell Labs visiting scholar, to a quite distinguished audience of management and staff. He was told a regular position would be awarded only after an acceptable performance. As you might expect, if you have ever seen Capasso lecture, his presentation was energetic, competent, and very well received. The staff position was secured and one of Capasso's long time career dreams was now fulfilled.

One of the advantages of Bell Laboratories, and a key reason Capasso appreciated a permanent position there, was not the monetary resources—Capasso claims that many European labs at the time had much more funding to spend on equipment. It was the meritocratic structure at Bell, which allowed anyone who was successful scientifically, to rapidly move up the corporate or scientific ladder. As you effectively broke new ground, your personnel resources and access to funding grew. However intense competition somehow coexisted with a highly collaborative and interactive environment that crossed disciplinary boundaries and fostered fast paced innovation.

At about the same time as Capasso arrived at Bell, another Bell group created a light emitting diode [14], and later avalanche photodiodes, from InGaAsP [15], a hot new material system that was being widely used for long wavelength optical laser sources. Capasso was also well aware of the engineered quantum well structures that had been envisioned in 1970 by Leo Esaki and Raphael Tsu at IBM [16] and which by 1976 were being actively developed at Bell and IBM [17]–[19], amongst other places. He began to think about whether such a structure might be used to *engineer* a better avalanche photodiode, one in which electrons were the dominant impact ionizing particles.

At this point Capasso had the first of several career-catapulting epiphanies. He reasoned that what was needed was an artificial material structure that would impart energy to the electrons as they traversed the semiconductor, but not to the holes. He further realized that this might be accomplished if one could design a "ski slope" like energy diagram that would add an extra "swish" to the passing electrons. By growing many alternating layers with spatially varying bandgap, he could create successive energy steps within the crystal that took the form of a *sloped-staircase* for the electrons only. Electrons going down this sloped-staircase, would gain an abrupt energy boost as they traversed each step and then could readily generate an electron–hole pair by impact ionization. Holes, on the other hand, saw a much smaller energy step and would therefore not impact ionize. The result was a novel low-noise avalanche photodiode device [20], [21]. This breakthrough concept—of a heterostructure composed of a descending staircase cascade or a *graded bandgap*, would become the basis for a whole class of newly engineered electron transport structures that would eventually lead to the quantum cascade laser (*but let's not get ahead of ourselves*).

Amidst many naysayers, Capasso worked out the theory, and performed the experiments that quickly proved that energy steps in semiconductor heterostructures could enhance the electron impact ionization rate [22], [23]. He also invented other types of low noise avalanche photodiodes based on the spatial separation of electrons and holes in semiconductors of different bandgaps [24], [25].

Capasso's work on multilayered structures really began to take off as molecular beam epitaxy was perfected. Capasso began to collaborate closely with one of the experts in this emerging area, Alfred Cho, often referred to as the *Father of Molecular Beam Epitaxy*. These were the Golden Days of heterostructures, and for Capasso, a candy store of opportunities and inventions. Over the next ten years Capasso and his collaborators contributed a dozen books and book chapters, more than 100 papers, and over 20 patents on graded bandgap physics and devices!

By 1982, word had spread about the multilayered heterostructures, and more tailored bandgap devices were appearing. Capasso and his colleagues at Bell went on to demonstrating avalanche photodiodes that showed photomultiplier-like behavior [26], [27]; the invention and demonstration of engineered heterojunction bipolar transistors [28], [29] and resonant tunneling transistors [30]–[33], stimulating new research in multiple valued logic and multilevel coding; the demonstration of tunable band discontinuities using doping interface dipoles [34], [35], making it possible for the first time to tailor a fundamental property of heterojunctions; observations of extra-large photoconductive gain by effective mass filtering [36]–[38]; the first observation of sequential resonant tunneling through a quantum well superlattice [39]; observation of negative differential conductance by field induced localization in superlattices [40]; the detection of resistance resonance associated with quantum interference in coupled quantum wells [41]; coupled quantum well semiconductors with the highest observed intersubband nonlinear optical susceptibilities, χ^3 [42], later used by Capasso and his group within the active region of quantum cascade lasers to enhance functionality and tuning agility; and the observation of electronic bound-states in the continuum above a potential well, verifying a 1929 prediction by Von Neumann and Wigner [43]. All of these discoveries were enabled by tailored *bandgap engineering* [44], and it was an exhilarating time for Capasso and his small, but extremely talented group at Bell.

In the early 1990s, Capasso came back to thinking about solid-state lasers—his first assignment when he arrived at Bell Laboratories. Quantum-well lasers had been around since the 1970s, but they had a fairly simple confinement structure and were limited in performance to the shorter wavelengths. There had been some early Russian theoretical work in 1971 by Kazarinov and Suris [45] proposing the use of intersubband transitions in a quantum well superlattice for long wavelength lasing. This got Capasso thinking about quantum barrier resonant tunneling, which he had demonstrated in transistors almost ten years earlier [31], [46]. For the second time, he was struck by a career making innovation—the application of the staircase quantum well structure to stimulate *photon emission*, rather than impact ionization.

Bell Laboratories had some of the best MBE facilities and growers in the world at the time. They were also working on what turned out to be an ideal material system for such a laser structure—AlInGaAs/InGaAs on InP, pioneered by Al Cho, who had already been collaborating with Capasso on structures made of this material for many years. This and related heterostructures on InP, were being developed as a technology platform for the telecom industry. As an optoelectronics building block, AlInGaAs/InGaAs heterostructures had already seen significant investment. Capasso brought in new group members Jerome Faist and Carlo Sirtori, to join his long time collaborative team of Alfred Cho, Deborah Sivco, and Albert Hutchinson, and they began concentrating on mid-IR lasers.

A wonderful review of the technical hurdles, scientific innovations and personal stories of the events leading up to the first demonstration of the Quantum Cascade Laser (QCL) can be found in Chapter 6 of the book, *Stuff, The Materials the World is Made of* by Ivan Amato [47] as well as in a feature article in *Scientific American* by science writers Elizabeth Corcoran and Glenn Zorpette [48]. The first observations of electroluminescence appeared in February 1994 [49], and the now classic paper on the Quantum Cascade Laser (with more than 2300 Web of Science citations) came out shortly afterwards in April 1994 [50].

The quantum cascade laser was the first laser device whose properties were determined not primarily by the material, but by the material thickness. This was a truly ground breaking innovation and again set the stage for a whole plethora of novel devices and exciting new physics. With the growth and materials expertise available at Bell, the field was wide open for the next ten years, and Capasso and his group came out with paper after paper, often making major strides in performance as well as new structures and applications. [51]–[53] are some key references recommended by Capasso himself.

It took almost three years from their first demonstration [50], to achieve pulsed operation at room temperature [54]–[56], and another five years before the first demonstration of continuous wave room-temperature output power [57]. Meanwhile the continuous march towards longer and longer wavelength operation was on. This started at Bell, but soon expanded to other research groups. Capasso recalls the "friendly" competition to make QC lasers that worked at wavelengths beyond 30 microns. Four groups were involved—his own group at Bell; two of his former group members, Jerome Faist, who was then at University of Neuchâtel, Switzerland, and Alessandro Tredicucci, who was at the Scuola Normale Superiore in Pisa, Italy; and Qing Hu at MIT, Cambridge, Massachusetts, who was investigating an alternative quantum well structure for lasing applications. It was Tredicucci who first reached the THz regime in 2002: *4.4 THz pulsed operation at 50 K ambient temperature with 2 mW of peak output power* [58]. Since then, quantum cascade lasers have dominated the spotlight in THz source development, with dozens of research groups springing up around the world and many new approaches to achieving higher power, higher temperature, continuous tuning, and operation down to frequencies below 2 THz [59]–[62].

This surge, both in the growth of research, as well as applications for the quantum cascade laser, was spurred by Capasso's actions after the very first mid-IR results came out. In thinking about his earlier experiences with the graded bandgap photodiodes, Capasso realized no one would pay any attention to the QCL unless they had access to the devices. In 1996, he started to give away the lasers to quality scientists who could use them in their research. Not surprisingly this led to collaborations with some notable spectroscopists and chemists: Bob Curl [63] and Frank Tittel at Rice, John Hall at NIST, Richard Zare at Stanford, and many others. He also became involved with several companies and government labs, including Pacific Northwest National Labs, that began using QCL's for security applications. DARPA came in as a major sponsor, which helped Capasso expand his research group and his outreach.

It was not until years later that Capasso realized what he had accomplished. No one had ever made a practical high performance mid-IR semiconductor laser, let alone a solid-state device with watts of output power at room temperature. The closest competitor was the table-top sized, kW draw, CO_2 gas laser, and even Chandra Kumar Patel, inventor of the CO_2 laser, was converted over to the QC laser before too long.

Quantum cascade lasers represent the peak accomplishment of band structure engineering. Perhaps Capasso himself best described the impact of the quantum cascade lasers in a response to a recent request for information: “QCL’s are the first lasers in which the emission wavelength can be tailored over an extremely broad range using quantum design. They have revolutionized mid-infrared photonics, as they represent the first high performance and reliable semiconductor lasers for this technologically and scientifically important spectral region. They are finding widespread use in scientific and industrial applications: high-resolution spectroscopy, chemical sensing and trace gas analysis, atmospheric chemistry, combustion and medical diagnostics. Numerous companies are now commercializing QC lasers and related sensors.”

After THz QCL’s became established, Capasso continued to make significant advances in their design and applications. He is not convinced that the approaches being followed today in other research groups, will allow realization of the goal of room temperature operation [64]. Capasso has proposed alternative techniques based on difference frequency mixing in which he cleverly incorporates an engineered crystalline structure with a large nonlinear susceptibility (χ^2) in the active region itself [65]–[67] (yet another example of *Physics by Design*!). He has also made major strides in improving the output power, tuning, and beam efficiency of the QCL chip through the implementation of facet engineering techniques to realize plasmonic 1D and 2D collimators (subwavelength diffraction gratings made with extremely small grooved surfaces), that can be used to guide and shape the mid-IR and THz light exiting from the QCL cavity [68]–[72]. This work has already opened up a whole new field of wave front engineering.

Capasso is most interested in applying QCL’s to significant real world problems. Towards that end he has been working closely with Hamamatsu Photonics to develop more advanced QCL’s in the mid-IR based on his wave front engineering solutions for improved QCL performance. He also started his own company in 2009, EOS Photonics[2], to bring to market broadband quantum cascade lasers for a wide range of chemical sensing applications.

On the science side, Capasso has teamed up over the years with climatologists and atmospheric chemists, to provide QCL’s for aircraft and even proposed satellite programs, that use these mid- and far-IR sources for performing remote sensing and *in situ* studies of the Earth’s atmosphere [73]; and with spectroscopists to demonstrate ultrahigh sensitivity detection of chemical constituents (at the part per billion level) in gases [74]–[76]. He has also worked with medical experts to develop QCL’s for biological applications [77], [78], spectroscopic breath analysis, pollutant monitoring [79], communications [80], [81], and even stand-off spectroscopy for forensic analysis. In fact, it is hard to find an application area where QCL’s at some wavelength, do not play a role. Capasso believes very strongly in these applications, and is extremely proud of the fact that he can (and does) make an impact that goes well beyond the laboratory.

While at Bell Laboratories, Capasso had moved rapidly up the technical management ladder, becoming a Department Head for Quantum Phenomena and Device Research in 1987, a post he held through the 1996 transition of AT&T Bell Laboratories to Lucent Technologies. In 1997, he became department head for Semiconductor Physics at Lucent, and in 2000, he was promoted to Vice-President for Physical Research at Lucent. Throughout this period he continued to work feverishly on his research, although at night! After a long day, he would return home to spend the evening with his wife and two children, wait until it was quiet, and then sneak back to the lab for some quality work time. He walked the difficult path to balancing family and work, by simply leaving out sleep! Many graduate students will appreciate (or at least sympathize with) this model, which Capasso sticks to today—he claims one of the few benefits of getting older is the fact that he needs even less sleep now.

As a VP at Lucent, Capasso was involved with some major business related development activities (lasers for cable televisions, for example) and in dealing with some very visible personnel issues—including the infamous Jan Hendrik Schön scientific fraud case[3]. Despite the long days and nights, and the non-technical distractions, Capasso loved his time at Bell. He learned much about the importance of research focused on application, and about the blending of science and industry. When Lucent began to seriously suffer from the telecom meltdown in 2001, Capasso somewhat reluctantly took a call from his former boss at Bell, Venkatesh (“Venky”) Narayanamurti, then Dean of the Division of Engineering and Applied Sciences at Harvard. At the end of 2002, he and his wife moved several hours north to Cambridge, Massachusetts, where Capasso took up a faculty position in the Harvard Division (now School) of Engineering and Applied Sciences.

Just before leaving Lucent, Capasso had gotten interested in the Casimir force (the quantum electrodynamic attraction between uncharged metal plates in vacuum), as a possible new tool for his engineering design toolbox. On a nanometer scale, this force can be the dominant interaction between conductors. For a physicist who had spent a good deal of time building nanoscale structures, this was a very relevant subject for investigation.

Capasso focused on basic phenomenological studies using MEMS to measure the Casimir force with high precision [82], and then designed several novel devices based on the effect, including actuators and nonlinear oscillators [82], [83]. He also studied the effect of the skin depth on the Casimir force [84], and the Casimir effect in a fluid [85]. He then turned to performing the first measurements of the repulsive Casimir force (to date, only attractive forces had been measured) [86]. True to form, Capasso was trying to use the technological tools available to him to engineer materials and shapes that would take advantage of, or manipulate these naturally present quantum electrodynamical forces [87]–[89].

Although Capasso continues to return to, and to publish on topics that he has explored throughout his long and distinguished career, his most recent innovations have been in yet another new area he has helped create with his *engineering by design* approach to science: *flat optics*. He began by using engineered “metainterfaces” (such as subwavelength spaced optical antennas integrated onto a flat surface [90]) to introduce phase

[2][Online.] Available: http://www.eosphotonics.com

[3]See, for example, http://en.wikipedia.org/wiki/Sch%C3%B6n_scandal

shifts to impinging radiation. This lead to the demonstration of generalized laws of reflection and refraction [91], [92]—*Optics by Design!*

These newly designed "metasurfaces" have been used for beam shaping in the optical, IR, and recently at THz wavelengths, and many new papers are coming out of this work ([93], [94] to list just a couple). This new development has opened up the optical regime to creating what used to be possible only at microwave frequencies—reflect- and transmit-arrays. The ability to engineer phase during beam propagation, allows the construction of many traditional optical components and the design and invention of new optical elements, all produced on a completely flat surface through nanodesign. The work has already made a huge splash in the optical research community. When the paper on flat lenses [93] was published, Capasso's web page had so many hits, it almost brought down the School of Engineering and Applied Sciences website—*a la Mark Zuckerberg!*

Finally, Capasso and his students have just recently discovered another new effect through the engineering of ultrathin surfaces—the control of the wavelength of reflected and absorbed light using plasmonic based coatings to selectively "color" a surface [95], [96].

I could go on and on, as the most recent of Capasso's creative engineering seems to be growing in popularity and application even faster than his QCL developments. For those who want to keep a close eye on this *Da Vinci of nanoengineering*, don't let a month go by without a look at Capasso's website: www.seas.harvard.edu.

Harvard turned out to be a perfect place for Capasso. The academic freedom and emphasis on cross-disciplinary research within the university environment suited him to a tee. As we talked about topics other than technical accomplishments, we naturally came to the subject of the state and health of scientific research in the US (a favorite subject of mine), and in the world generally. Capasso showed me his folder of more than 100 major research proposals he has already completed in his first decade of University employment. I took no comfort in the knowledge that someone already so accomplished, was still spending such an enormous amount of time and personal resources, just to keep basic funding flowing into his group.

Capasso pointed out that in his contracts with private companies, he actually has more freedom to use resources where he deems them most beneficial, than he has with his government grants. This is not the first time I have heard such a story, and it begs the question of whether our government sponsors, who supposedly work in the best interests of scientific progress, have perhaps lost the capacity to trust the judgment of the very people they propose to lead the country in innovation.

On the subject of creativity and "out-of-the-box" thinking, Capasso is very certain that cross-disciplinary work is essential. He professed that nature does not make divisions in science, man does. The artificially established disciplines that we all organize around; physics, chemistry, biology, math etc., do not individually reflect the real world problems that need to be solved, and can in some cases, actually impede technological innovation. In a Correspondence Reply to an article in *Nature* some years ago [97] he stated, "If scientific knowledge was not an objective description of reality, but merely a social construct, we would not have technological realities such as transistors, microprocessors, personal computers and the Internet, or semiconductor lasers, fibre optics and compact disc players in addition to radios, cars and jets." Individuals have to learn to bridge technical and topical boundaries in order to solve real problems and to make the most impact. "*Creativity is king in science*."

This emphasis on solving problems by crossing boundaries, includes the boundary between academics and business. His many years at Bell, and especially his years as a VP at Lucent, have reinforced his already prevalent way of looking at science: as a profession for problem solvers. This applies whether those that choose it as a career are focused on the grand challenge of understanding or manipulating nature, or the equally valuable challenge of developing useful products for the betterment of humankind. Capasso tries to teach his students not just subject matter, but problem solving. He does so through a very interactive technique that he credits to Harvard physicist Eric Mazur [98]. He also emphasizes that problems need not be esoteric to be interesting and worthy of the investment in time of a creative individual.

As a final note, I agree with Capasso completely when he stated that, "Problems are big today and need multidisciplinary solutions." We might also add, that one tried and true Capasso method for overcoming nature's limitations and solving some major world problems, is to use the tools of engineering to enhance what nature cannot deliver. *Physics by Design, nobody does it better!*

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After doing research in fiber optics at Fondazione Bordoni in Rome, he joined Bell Laboratory, Holmdel NJ, USA, in 1976. In 1984, he was made a Distinguished Member of Technical Staff and in 1997 a Bell Labs Fellow. At Bell, he held the posts of Head of the Quantum Phenomena and Device Research Department and the Semiconductor Physics Research Department between 1987 and 2000. From 2000 to 2002 he was Vice President of Physical Research at Lucent Technology. In 2003, Capasso left Bell to take up a faculty position at Harvard University, Cambridge, Massachusetts, USA, where he now heads a large group of extremely talented graduate and post-graduate students. In collaboration with a wide range of multi-disciplinary scientists and engineers, he has made a series of very important contributions to solid-state physics, devices, materials, and applications. His pioneering work on band structure engineering led to the development of new low noise quantum well avalanche photodiodes, resonant tunneling transistors, new memory devices and lasers. He and his collaborators invented and demonstrated the quantum cascade laser (QCL), which, unlike conventional semiconductor lasers, relies on the energy separation between conduction band quantized states in cascaded quantum wells. QCLs have become the most widely used sources of mid-infrared radiation for chemical sensing and spectroscopy and are now commercially available. Capasso also made significant contributions to the understanding and application of the Casimir force, demonstrating for the first time, the repulsive Casimir force. Capasso's current research is focused on a whole new field of engineered surfaces that can be used to make flat optical components by phase control on a surface. Prof. Capasso has presented more than 400 talks at conferences, workshops, laboratories and companies around the world. He has published more than 450 papers in refereed journal and conference digests; written, edited or contributed to more than 25 books; holds more than 60 patents; and collaborates with dozens of top institutions, government laboratories, companies and exceptional researchers and educators worldwide.

Prof. Capasso is a Fellow of the American Academy of Arts and Sciences, the Institute of Physics (UK), the American Association for the Advancement of Science, the International Society for Optical Engineering (SPIE), the Optical Society of America, the IEEE and the American Physical Society. He is also an Honorary Member of the Franklin Institute and a Member of the National Academy of Engineering and the National Academy of Sciences. He is a foreign member of the Accademia dei Lincei, the world's first scientific academy, which had Galileo Galilei as one of its founding members. Dr. Capasso holds 4 honorary doctorates, and his awards include: the 2011 Galileo Galilei Medal of the Italian Society for Optics and Photonics, the 2011 Jan Czochralski Award of the European Materials Research Society, the 2010 Julius Springer Prize in Applied Physics, the 2010 Berthold Leibinger Zukunft Prize (Future prize), the 2005 King Faisal International Prize for Science, a 2005 Gold Medal of the President of Italy for meritorious achievement in science, the 2004 Edison Medal from the IEEE, the 2004 Arthur Schawlow Prize in Laser Science of the American Physical Society, the 2004 Tommasoni and Chisesi Prize for Outstanding Achievements in Physics, the 2002 Duddell Medal and Prize of the Institute of Physics, the 2001 Robert Wood Prize of the Optical Society of America, the 2000 Willis E. Lamb Medal for Laser Physics and Quantum Optics, the 1991 IEEE David Sarnoff Award in Electronics, and many others. Professor Capasso is also a co-founder and chairman of the board of a private company, EOS Photonics, that is engaged in commercializing QCL devices for a wide range of applications. He continues to teach and to perform research as the Robert Wallace Professor of Applied Physics in the Harvard school of Engineering and Applied Sciences.